THE FORMATION OF THE FIRST STARS [1]

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ABSTRACT

The first bound star-forming systems in the universe are predicted to form at redshifts of about 30 and to have masses of the order of $10^6\,\mathrm{M}_\odot$. Although their sizes and masses are similar to those of present-day star-forming regions, their temperatures are expected to be much higher because cooling is provided only by trace amounts of molecular hydrogen. Several recent simulations of the collapse and fragmentation of primordial clouds have converged on a thermal regime where the density is about 10^3–$10^4\,\mathrm{cm}^{-3}$ and the temperature is about 300 K; under these conditions the Jeans mass is of the order of $10^3\,\mathrm{M}_\odot$, and all of the simulations show the formation of clumps with masses of this order. The temperatures in these clumps subsequently rise slowly as they collapse, so little if any further fragmentation is expected. As a result, the formation of predominantly massive or very massive stars is expected, and star formation with a normal present-day IMF seems very unlikely. The most massive early stars are expected to collapse to black holes, and these in turn are predicted to end up concentrated near the centers of present-day large galaxies. Such black holes may play a role in the origin of AGNs, and the heavy elements produced by somewhat less massive stars also formed at early times may play an important role in chemically enriching the inner parts of large galaxies and quasars.

1. INTRODUCTION

How did star formation begin in the universe? And can we make any credible predictions about the properties of the first stars? Recent years have seen great advances in our theoretical understanding of the origin of structure in the universe and the formation of galaxies, and on the observational front we now have observations extending out to redshifts greater than 5 and looking back to the first billion years of the history of the universe. It is clear that much had already happened during that period: galaxies, or at least parts of galaxies, had already appeared on the scene; the first quasars had already formed; and the intergalactic medium had become ionized. Furthermore, the densest parts of the universe, including quasars, had already become significantly enriched in heavy elements. Most of the heavy elements in large galaxies like our own appear in fact to have been produced at relatively early times, and there has been only modest subsequent

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enrichment, leaving a general paucity of metal-poor stars compared with the predictions of simple models; this is the long-standing and apparently ubiquitous 'G-dwarf problem'. Finally, a far-infrared background radiation has been observed which contains half of the present radiative energy density of the universe, and which is believed to have been produced mainly by dust-obscured star formation at high redshifts. All of these observations reflect in various ways the effects of early star formation, and some of them, particularly the rapid enrichment in heavy elements, would be easiest to understand if early star formation had produced preferentially massive stars. Therefore there has been great interest in understanding the earliest stages of star formation in the universe, and especially in understanding what the typical masses or mass spectrum of the first stars might have been.

2. THE FIRST STAR-FORMING SYSTEMS

Current cosmological models now provide us with a framework for addressing the problem of early star formation and specifying plausible initial conditions. Recent progress in cosmology has led to a set of variants of the standard CDM model which, while differing in quantitative details, all make similar predictions about the way in which structure emerged in the early universe. In all of the currently viable models, cosmic structure is built up hierarchically, and larger systems are assembled from smaller ones by the accumulation of matter at the nodes of a filamentary web-like network. These models provide a well-tested description of the development of galaxy clustering and large-scale structure in the universe, but they do not yet predict correctly the properties of individual galaxies and have not been tested at all on much smaller scales; therefore we cannot yet be confident that they predict in a quantitatively correct way the properties of the first star-forming systems. However, in all models, qualitatively similar things are expected to happen on smaller scales at earlier times, so we expect that the first star-forming systems were created in a similar way by the accumulation of matter at the nodes of a filamentary network. The various currently viable models can then be used to make extrapolations to smaller scales and earlier times that we can use as working hypotheses to investigate early star formation. We can also hope that the physics of early star formation was simpler than that of present-day star formation because the important physical processes involved only various forms of hydrogen, and because turbulence and magnetic fields might not yet have been introduced by the effects of prior star formation.

Current models predict that the first bound systems capable of forming stars appeared during the first 10^8 years of the history of the universe at redshifts between 50 and 10, and that they had masses between about 10^5 and $10^8\,M_\odot$ (Peebles 1993; Haiman, Thoul, & Loeb 1996; Tegmark et al. 1997; Nishi & Susa 1999; Miralda-Escudé 2000). Most of this mass is dark matter, and the gas mass is about an order of magnitude smaller. The predicted radii of these first star-forming systems are between 10 and 500 parsecs, and their internal velocity dispersions are between about 5 and 25 km/s. These properties are not greatly different from those of present-day star-forming regions in galaxies, including giant molecular clouds, large complexes of gas and young stars, and starburst regions. However, an important difference is that the temperatures of the first collapsing clouds must have been much higher than those of present molecular clouds because of the absence of any heavy elements to provide cooling. In the metal-free primordial clouds, the only possibility for cooling below $10^4\,$K is provided by trace amounts of molecular hydrogen comprising up to about 10^{-3} of the total hydrogen abundance, and H_2 molecules cannot cool the gas significantly below 100 K; the calculated temperatures of primordial clouds are in fact mostly in the range 200–1000 K (Anninos & Norman 1996; Haiman, Thoul, & Loeb 1996; Tegmark et al. 1997; Nakamura & Umemura 1999; Abel, Bryan, & Norman 1999; Bromm, Coppi, & Larson 1999). Thus, thermal pressure must have played a much more important role in primordial star formation than it does

in present-day star formation; in particular, the Jeans mass must have been much larger in the primordial clouds than it is in present-day clouds, since the densities of the first star-forming clouds were not very different from those of present clouds, while their temperatures were much higher.

3. THERMAL PROPERTIES OF THE PRIMORDIAL GAS

Three different groups simulating the collapse and fragmentation of primordial star-forming clouds have recently obtained consistent results for their thermal behavior, and these results will be summarized briefly here. The most realistic calculations are those of Abel et al. (1998) and Abel, Bryan, & Norman (1999; hereafter ABN), who have started with a full cosmological simulation including a detailed treatment of the gas physics, and have followed the evolution of the first recollapsing density peak through many orders of magnitude in density using a progressively finer grid. At the latest stage reached, this calculation is well on the way to modeling the formation of a single massive star or small group of stars. Somewhat more idealized is the simulation by Bromm, Coppi, & Larson (1999, 2000; hereafter BCL) of the collapse of a simple 'top-hat' cosmological density perturbation with a standard spectrum of density fluctuations and a typical angular momentum; this calculation uses an SPH technique intended to follow the formation of a small group of dense clumps. In this simulation the gas collapses to a disk which then fragments into filaments and clumps, and the collapse of the clumps is again followed through a large increase in density. The most idealized and least cosmology-dependent calculations are those of Nakamura & Umemura (1999, 2000; hereafter NU), who have simulated the collapse and fragmentation of gas filaments with initial densities and temperatures appropriate for primordial clouds; these authors have followed the collapse of these filaments to higher densities than the other groups and into the regime where opacity becomes important.

In the simulations of ABN and BCL, the initial recollapse of a 3σ density peak at a redshift of ~ 30 compresses the gas and heats it to temperatures above 1000 K; this in turn increases the H_2 formation rate and causes the H_2 abundance to rise from its initial value of about 10^{-6} to a quasi-equilibrium value of about 10^{-3} of the total hydrogen abundance. The additional molecular hydrogen thus created cools the gas in the flattened disk-like configuration resulting from the collapse to a temperature of about 200–300 K, but the temperature then begins to rise again in the dense clumps that form, reaching $\sim$500–800 K at the highest densities attained. The simulations by NU of the fragmentation of filaments do not start with any overall collapse and therefore do not show the same initial rise and fall in temperature, but they nevertheless yield similar H_2 abundances and similar temperatures of $\sim$300–500 K over a similar range of densities. All three sets of calculations converge into the same density-temperature regime after the initial collapse has stopped and any flattened or filamentary configuration produced by it is beginning to fragment into clumps; at this stage, the density is about 10^3–10^4 atoms per cm^3 in all cases, and the temperature is about 200–300 K. Under these conditions the Jeans mass is of the order of $10^3\,M_\odot$, and all of these simulations find that clumps are formed with masses of this order.

Thus, while more work is needed to verify the generality of these conclusions, it appears that the predicted thermal behavior and fragmentation scale of primordial clouds are fairly robust results, and depend mainly on the gas physics and not on the simulation techniques or the cosmological model assumed. An important feature of the gas physics that may help to account for this convergence of results is that at densities greater than $10^4\,\mathrm{cm}^{-3}$ the level populations of the H_2 molecule come into thermodynamic equilibrium, causing the density dependence of the cooling rate to saturate and the cooling time to become independent of density; as a result, the cooling time again becomes longer than the free-fall time at the higher densities, and the collapse is significantly slowed down from a free fall. A further effect that may also be relevant is that the gas

is still confined partly by the gravity of the dark matter when it begins to fragment into clumps, so that it is not yet fully self-gravitating and lingers for a time in this favored density-temperature regime, allowing more time for the Jeans scale to be imprinted on the dynamics.

4. FRAGMENTATION AND THE STELLAR MASS SCALE

During the collapse of the 'top-hat' density perturbations studied by BCL, the density fluctuations in the dark matter grow unimpeded, while the gas at first retains a smoother distribution because it is warmer; however, as the density of both the dark matter and the gas increase, the gas increasingly responds to the dark matter density fluctuations and begins to develop a similar clumpy structure. After about a free-fall time, the dark matter 'virializes' to form a small dark halo, while the gas settles into a smaller rotationally supported disk within this halo. For a system with a total mass of $2 \times 10^6\,\mathrm{M}_\odot$ and a gas mass of $10^5\,\mathrm{M}_\odot$ collapsing at a redshift of ~ 30, the radius of this disk is about 15 pc. Irregularities in the disk develop into filamentary spiral structure, and the filaments then fragment into massive clumps. The density fluctuations in the dark matter thus appear to trigger the growth of structure in the gas and may determine where the most massive clumps will form, but once the gas has settled into a disk, its subsequent evolution appears to depend more on the thermal properties of the disk than on the initial conditions for the collapse. In particular, the masses of the clumps depend mainly on the Jeans scale in the disk and not on the nature of the initial density fluctuations. The most important effect of the dark matter may then simply be that its gravity confines the gas in a disk long enough for gravitational instabilities in the disk to play a significant role in its evolution.

The full cosmological simulation of ABN shows qualitatively similar behavior, but it exhibits filamentary structure from the beginning and yields a single dominant central clump in the first recollapsing density peak. The rezoning technique used by these authors follows with ever-increasing resolution the collapse of this clump, and at the last stage reached, it has developed a slowly contracting core with a mass of about $100\,\mathrm{M}_\odot$ surrounded by a flattened envelope with a mass of about $1000\,\mathrm{M}_\odot$ in which rotational support is important. The central core continues to contract nearly spherically and shows no sign of fragmentation into smaller objects. It is possible that additional objects might form in the flattened disk-like region around it, but the calculation focuses on resolving the collapse of the central core. The introduction of 'sink particles' in the simulation of BCL allows the calculation to be carried farther and the formation of a small group of objects to be followed, at the expense of not resolving what happens at the highest densities. Again, the clumps formed show no sign of fragmenting into smaller objects. The masses of these clumps are typically of the order of $10^3\,\mathrm{M}_\odot$, with a range extending from the resolution limit of $\sim 10^2\,\mathrm{M}_\odot$ to more than $10^4\,\mathrm{M}_\odot$. Experiments with a variety of initial conditions suggest that a typical clump mass of $\approx 10^3\,\mathrm{M}_\odot$ is a rather general result even when the overall structure of the system becomes much more complex than the simple disk discussed above.

The simulations of NU also find that primordial gas filaments tend to fragment into clumps with masses of the order of $10^3\,\mathrm{M}_\odot$. If some of the gas condenses into much thinner and denser filaments before fragmenting, objects with much smaller masses can also be formed. The simulations do not yet indicate how much mass might fragment into smaller objects in this way, but it seems unlikely that a major fraction of the total mass will be involved. A question of great interest is whether any stars smaller than a solar mass can be formed; Uehara et al. (1996) suggested that such stars cannot form under primordial conditions because the onset of high opacity to the H_2 cooling radiation sets a minimum fragment mass that is approximately the Chandrasekhar mass, somewhat above $1\,\mathrm{M}_\odot$. NU confirm this result from a more detailed treatment of the radiative transfer problem, and they conclude that fragmentation can continue down to a minimum mass between 1 and $2\,\mathrm{M}_\odot$.

If there is indeed a minimum mass for metal-free stars that is larger than $1\,M_\odot$, this would be a very important result because it would imply that we should see no metal-free stars at the present time, even if large numbers of such stars had once been formed, since all of these stars should by now have evolved.

5. STAR FORMATION THEN AND NOW

It may be useful to compare early star formation with present-day star formation in discussing the expected fragmentation scale and the likely masses of the stars formed. Since the predicted sizes and masses of the first star-forming systems are not greatly different from those of present-day molecular clouds, their average densities and internal pressures are also not very different. In fact, the typical gas pressure in the disks discussed above, which have an average density of $\sim 10^3\,\mathrm{cm}^{-3}$ and a temperature of $\sim 300\,\mathrm{K}$, is about the same as the typical pressure in present-day cold molecular cloud cores, which have a density of $\sim 3 \times 10^4\,\mathrm{cm}^{-3}$ and a temperature of 10 K. Thus, if one calculates the Jeans mass from the temperature and pressure of a star-forming cloud, for example by taking the mass of a marginally stable Bonnor-Ebert sphere which varies as the square of the temperature and inversely as the square root of the pressure, this mass is larger in primordial clouds than in present clouds just by the square of the temperature. Since the Jeans mass in present-day molecular clouds is of the order of one solar mass (see below), and since the temperature is about 30 times higher in the primordial clouds, the Jeans mass in these clouds is predicted to be about 1000 times higher, or about $10^3\,M_\odot$, as was noted above. Note that the Jeans mass will remain higher than present values even after the first heavy elements have been introduced, since the temperature still cannot fall below the cosmic background temperature, which is 57–85 K at redshifts of 20–30; this is nearly an order of magnitude higher than the present-day temperatures of cold molecular cloud cores, implying a Jeans mass that is still almost two orders of magnitude higher than present values, again assuming a similar pressure (Larson 1998).

How relevant is the Jeans mass in determining typical stellar masses? This question has been controversial in recent years, and it has been debated whether the present characteristic stellar mass of the order of one solar mass is determined by the scale of cloud fragmentation or by the onset of strong outflows that terminate the accretional growth of protostars at some stage (Meyer et al. 2000). Some recent evidence suggests that stellar masses are closely related to the masses of the dense clumps observed in star-forming molecular clouds, supporting the view that the characteristic stellar mass is determined by the scale of cloud fragmentation. Motte, André, & Neri (1998) have observed many small dense clumps in the ρ Ophiuchus cloud that have masses between 0.05 and $3\,M_\odot$, and they find that the mass spectrum of these clumps is similar to the IMF of local field stars, including the flattening below a solar mass that is indicative of a characteristic mass around one solar mass. The mass spectrum of these clumps has also been compared with that of the pre-main-sequence stars in the same cloud by Luhman & Rieke (1999), and they find that the two functions are indistinguishable from each other and from the IMF of the local field stars. This suggests that stars form with masses similar to those of the observed dense clumps in molecular clouds, and that the characteristic stellar mass is therefore determined by the typical clump mass. This mass is in turn found to be similar to the Jeans mass calculated from the typical temperature and pressure in molecular clouds, which is approximately one solar mass or slightly less (Larson 1985, 1996, 1999, 2000; Meyer et al. 2000).

Since the predicted thermal behavior of primordial clouds is qualitatively similar to that of present-day molecular clouds except for temperatures that are about 30 times higher at a given pressure, similar conclusions might be expected to hold for primordial clouds, with masses about three orders of magnitude larger for both the clumps and the stars formed. This suggests that the

first stars were very massive objects, with typical masses of perhaps several hundred solar masses. However, definite conclusions cannot yet be drawn about the masses of the first stars because the final fate of the clumps discussed above has not yet been determined. The possibility that they will fragment into many smaller objects has not been ruled out, even though this seems unlikely. In the present-day case, it appears on both observational and theoretical grounds that the fragmentation of collapsing Jeans-mass clumps is limited to the formation of at most a small multiple system, the typical outcome being the formation of a binary system (Larson 1995). Numerical simulations illustrating the formation of binary and multiple systems (e.g., Burkert, Bate, & Bodenheimer 1997) have usually assumed an isothermal equation of state, but the temperatures in the primordial clumps discussed above do not remain constant but rise slowly as the clumps contract, and this can only reduce the amount of subsequent fragmentation that occurs. However, even if further fragmentation is unimportant, it remains possible that significant differences from the typical present-day situation could arise because of the much higher stellar masses expected at early times; for example, radiative feedback effects such as the dissociation of H_2 molecules by ultraviolet radiation might reduce the efficiency of early star formation (Haiman 2000; Ferrara & Ciardi 2000), and they might also reduce the masses of the stars formed by preventing the accretion by them of most of the initial clump mass (Abel 1999).

In summary, it appears to be a fairly general result that the first star-forming clouds fragment into massive clumps with masses of the order of $10^3\,\mathrm{M_\odot}$ and temperatures of a few hundred K; this result depends mainly on the well-understood thermal physics of the gas and not on the details of the initial conditions or the simulation technique used. It also appears unlikely that these massive clumps will fragment into many smaller objects as they collapse to higher densities. The stars that form in them will then almost certainly be much more massive than typical present-day stars. The IMF of the first stars was therefore almost certainly top-heavy, and it seems very unlikely that a standard present-day IMF could have been produced. The first stars might typically have been massive ($\approx 10^2\,\mathrm{M_\odot}$) or possibly very massive ($\approx 10^3\,\mathrm{M_\odot}$) objects, perhaps similar in the latter case to the 'VMOs' studied by Carr, Bond, & Arnett (1984) and Bond, Arnett, & Carr (1984) and reviewed by Carr (1994). Of course, any predictions concerning the properties of the first stars are as yet untested by any direct observations, and we must await observations of very high-redshift objects with instruments such as NGST before we can know for sure whether the work that has been described here is on the right track.

6. POSSIBLE EFFECTS OF EARLY STAR FORMATION

How were the first star-forming systems related to the galaxies that we presently see, and what role might the first stars have played in accounting for the properties of the systems that we see? The first star-forming units probably cannot be identified with any presently observed systems, since they would have been too small and too loosely bound to survive or to retain any gas after forming the predicted massive stars. These stars would have evolved within a few Myr, and any whose masses were larger than about $250\,\mathrm{M_\odot}$ would have collapsed to black holes containing at least half of the initial stellar mass (Bond, Arnett, & Carr 1984; Heger, Woosley, & Waters 2000). If a significant fraction of the first stars had such large masses, much of the matter that condensed into them might soon have ended up in black holes of similar mass. Massive black holes formed in this way at early times could have had a number of interesting consequences, including seeding the formation of supermassive black holes in galactic nuclei and thus accounting for the origin of AGNs.

In standard hierarchical cosmologies, the first objects form preferentially in the densest parts of the universe, and they then become incorporated through a series of mergers into systems of larger

and larger size which eventually become present-day large galaxies and clusters of galaxies. The first 3σ density peaks are predicted to be strongly clustered on the scale of clusters of galaxies and significantly clustered even on the scale of individual galaxies, and this means that the first stars or their remnants should now be concentrated in the inner parts of large galaxies, which in turn are mostly in large clusters (Miralda-Escudé 2000; White & Springel 2000). That is, these objects should now be found mostly in places like the inner parts of M87 rather than in the outer halos of galaxies like the Milky Way. If massive black holes were present from early times in the dense regions that later became the inner parts of large galaxies, they might have become increasingly centrally concentrated because of the strong gravitational drag effects that would have been present in such regions. The most massive ones might then have served as the seeds for building up larger black holes by accretion, and mergers among them might also have contributed to building up very massive central black holes. If the present galaxies with large spheroids were built up by a series of mergers of smaller systems that already contained central black holes, these central black holes might have merged along with their host systems to form increasingly massive black holes at the centers of galaxies of increasing mass. It is conceivable that most of the remnants of the first stars could have ended up in this way in the supermassive black holes of AGNs; in this case, an understanding of early star formation could turn out to be very relevant to understanding the origin of AGNs.

The accumulation processes that build massive black holes in galactic nuclei might be analogous to the processes that form massive stars at the centers of star clusters. Massive newly formed stars are always found in clusters, typically near their centers, and this can only be understood if these massive stars were in fact formed near the cluster center (Bonnell & Davies 1998). Since the various accretion or accumulation processes that might increase stellar masses are most important in the dense central parts of forming clusters, while the Jeans mass is not unusually high there, this suggests that massive stars are built up by accumulation processes in clusters and are not formed by direct cloud fragmentation (Larson 1982; Bonnell, Bate, & Zinnecker 1998; Clarke, Bonnell, & Hillenbrand 2000; Bonnell 2000). The most massive stars may even be produced by collisions and mergers between less massive stars in the extremely dense cores of forming clusters (Bonnell, Bate, & Zinnecker 1998; Stahler, Palla, & Ho 2000). As is the case with galaxies, interactions and mergers among subunits may play an important role in driving accretion onto central objects and possibly causing them to merge, and this could lead to the formation of stars of increasing mass as clusters are built up by the merging of substructure (Clarke, Bonnell, & Hillenbrand 2000; Bonnell 2000; Larson 2000). Such processes might also account for the observed power-law upper stellar IMF; in the simple model suggested by Larson (2000), the most massive star accretes a fixed fraction (1/6) of the remaining gas each time two subunits merge, and this leads to a Salpeter-like upper IMF with a slope $x = 1.36$ in which the mass of the most massive star increases as the 0.74 power of the mass of the cluster. A modification of this model might be able to account for the fact that the masses of the nuclear black holes in galaxies are approximately proportional to the bulge mass, typically being about 0.005 times the bulge mass. If nuclear black holes are built up by the same kind of sequence of mergers and associated accretion events, and if the resulting black holes merge into a single object when their masses exceed $10^6\,M_\odot$, then the central black hole mass increases in proportion to the bulge mass for larger masses and is about 0.005 times the bulge mass, as observed. Thus there could be a close analogy between black hole formation in galactic nuclei and the formation of massive stars in clusters.

The first stars must also have produced the first heavy elements in the universe. While stars more massive than $250\,M_\odot$ are predicted to collapse completely to black holes without ejecting any heavy elements, somewhat less massive primordial stars would have exploded as supernovae and begun to enrich their surroundings with heavy elements. Stars with masses in the range between about 100 and $250\,M_\odot$ are predicted to be partly or completely disrupted by the pair-production

instability (Bond, Arnett, & Carr 1984; Heger, Woosley, & Waters 2000), producing an energetic supernova event and dispersing some or all of the heavy elements produced during their evolution. Thus such objects could plausibly have been the first sources of heavy elements. Metal-free stars with masses between about 35 and 100 $\mathrm{M_\odot}$ probably again collapse to black holes (Heger, Woosley, & Waters 2000), while stars with masses between 10 and 35 $\mathrm{M_\odot}$ can explode as type II supernovae, possibly providing a second source of heavy elements if significant numbers of such stars were formed at the earliest times.

The first star-forming systems were probably too short-lived and too weakly bound to retain any of the heavy elements produced, so the first systems capable of self-enrichment were probably larger systems that formed somewhat later as larger cosmological structures collapsed, incorporating some of the remnants and nucleosynthetic products of the first systems. The dwarf galaxies of the Local Group are found to have a minimum mass of about $2 \times 10^7\,\mathrm{M_\odot}$ (Mateo 2000), which is about the minimum mass needed for a galaxy to retain ionized gas. The retention of ionized gas is essential for subsequent star formation and chemical enrichment to occur because most of the gas in a galaxy is cycled many times through an ionized phase, and the dispersal and mixing of heavy elements also probably occurs mostly in an ionized medium. Preliminary calculations similar to those of BCL but with H_2 replaced as the dominant coolant by a low abundance of heavy elements suggest that in such circumstances there may be a threshold metallicity between 10^{-4} and 10^{-3} times the solar value below which no cooling occurs but above which some of the gas can cool to temperatures as low as the cosmic background temperature. This would reduce the typical masses of the dense clumps formed, but not to present-day values because the background temperature is still relatively high at high redshifts. For example, the first systems with masses as large as $2 \times 10^7\,\mathrm{M_\odot}$ are predicted to form at a redshift of ~ 25, and the cosmic background temperature at that redshift is 71 K. If it is still valid to assume a pressure similar to that in present-day star-forming clouds, the predicted Jeans mass is then about 50 $\mathrm{M_\odot}$, still much larger than present-day values, suggesting that star formation at high redshifts would still have produced a top-heavy IMF even after the first heavy elements had been introduced (Larson 1998).

Early star formation with a top-heavy IMF in those regions that later became the inner parts of large galaxies could help to resolve a number of problems regarding the chemical abundances of galaxies and quasars. The heavy-element abundances in galaxies increase systematically with mass up to the largest masses known, and they also increase radially inward in large galaxies of all types. Neither of these trends is fully explained by standard models assuming a universal IMF, even if gas flows are invoked, but both might be explained if early star formation with a top-heavy IMF enriched preferentially the inner parts of the largest galaxies. The nuclear regions of the largest galaxies contain the most metal-rich stars known, and quasars can be even more metal-rich, with metallicities up to 5 or 10 times solar. These high metallicities cannot be explained with a standard IMF, but they might be explainable if the nuclear regions of galaxies containing AGNs were enriched by massive stars formed at early times with a top-heavy IMF, as would be expected in the picture sketched above. Star formation with a top-heavy IMF during the formation of cluster elliptical galaxies, perhaps associated with merger-induced starbursts, could also help to explain the high metallicities of both the stars and the hot gas in clusters of galaxies (Zepf & Silk 1996; Larson 1998). As was noted by these authors, a top-heavy early IMF might in addition help to account for the observed far-infrared cosmic background radiation, which is believed to be produced mostly by obscured high-redshift massive star formation, without violating limits on the current density of low-mass stars in the universe (see also Dwek et al. 1998). Finally, we note that the 'G-dwarf problem' mentioned in the introduction might be solved or alleviated if such processes made a significant contribution to enriching galaxies generally, even outside the nuclear regions.

7. SUMMARY

The first theoretical studies of the formation of primordial or 'population III' stars based on current cosmological models with a full treatment of the relevant physics have been begun within the past few years, and work by several groups is continuing. These studies have obtained consistent results for the thermal behavior of the first star-forming clouds, implying a scale of fragmentation that is of the order of $10^3\,\mathrm{M}_\odot$, and all of the simulations have found the formation of clumps whose masses are of this order. This strongly suggests that the first stars were typically massive or very massive objects, that is, it suggests a very top-heavy early stellar IMF, although quantitative predictions are not yet possible. More work is needed to verify the generality of these results, and more work is also needed to follow the later evolution of the clumps and predict the masses of the stars that form in them, but it seems very unlikely that the earliest star formation could have yielded a normal present-day IMF. After the first massive stars had formed, the properties of star-forming systems and the universe must rapidly have become much more complex as many feedback effects came into play, but it appears that some of the properties of galaxies and quasars might be explainable as a result of early star formation with a top-heavy IMF occurring in the dense regions that became the inner parts of large galaxies. The coming years are sure to see much progress, both theoretical and observational, in the currently very active quest to understand early star formation.

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